

MAGNETO-RESISTIVE DEVICE INCLUDING SOFT SYNTHETIC FERRIMAGNET REFERENCE LAYER

BACKGROUND

[0001] The present invention relates to magneto-resistive devices. The present invention also relates to data storage.

[0002] Magnetic Random Access Memory ("MRAM") is a non-volatile memory that is being considered for short-term and long-term data storage. MRAM has lower power consumption than short-term memory such as DRAM, SRAM and Flash memory. MRAM can perform read and write operations much faster (by orders of magnitude) than conventional long-term storage devices such as hard drives. In addition, MRAM is more compact and consumes less power than hard drives. MRAM is also being considered for embedded applications such as extremely fast processors and network appliances.

[0003] A typical MRAM device includes an array of memory cells, word lines extending along rows of the memory cells, and bit lines extending along columns of the memory cells. Each memory cell is located at a cross point of a word line and a bit line.

[0004] The memory cells may be based on tunneling magneto-resistive (TMR) devices such as spin dependent tunneling (SDT) junctions. A typical SDT junction includes a pinned layer, a sense layer and an insulating tunnel barrier sandwiched between the pinned and sense layers. The pinned layer has a magnetization orientation that is fixed so as not to rotate in the presence of an applied magnetic field in a range of interest. The sense layer has a magnetization that can be oriented in first and second directions: the same direction as the pinned layer magnetization or the opposite direction of the pinned layer magnetization. If the magnetizations of the pinned and sense layers are in the same direction, the orientation of the SDT junction is said to be "parallel." If the magnetizations of the pinned and sense layers are in opposite directions, the orientation of the SDT junction is said to be "anti-parallel." These two stable orientations, parallel and anti-parallel, may correspond to logic values of '0' and '1.'

[0005] The magnetization orientation of the pinned layer may be fixed by an underlying antiferromagnetic (AF) pinning layer. The AF pinning layer provides a large

exchange field, which holds the magnetization of the pinned layer in one direction. Underlying the AF layer are usually first and second seed layers. The first seed layer allows the second seed layer to be grown with a (111) crystal structure orientation. The second seed layer establishes a (111) crystal structure orientation for the AF pinning layer.

SUMMARY

[0006] A memory device according to the present invention includes a data layer having a magnetization that can be oriented in first and second directions; and a synthetic ferrimagnet reference layer. The data and reference layers have different coercivities.

[0007] Other aspects and advantages of the present invention will become apparent from the following detailed description, taken in conjunction with the accompanying drawings, illustrating by way of example the principles of the present invention.

BRIEF DESCRIPTION OF THE DRAWINGS

[0008] Figure 1 is an illustration of a magnetic memory device according to the present invention.

[0009] Figure 2 is an illustration of hysteresis loops for data and reference layers of the magnetic memory device shown in Figure 1.

[0010] Figures 3a and 3b are illustrations of a synthetic ferrimagnet reference layer for a magnetic memory device according to the present invention.

[0011] Figure 4 is an illustration of a hysteresis loop for an individual ferromagnetic layer of the synthetic ferrimagnet reference layer.

[0012] Figure 5 is an illustration of a hysteresis loop for the synthetic ferrimagnet reference layer.

[0013] Figure 6 is an illustration of a first method of performing a read operation on the magnetic memory device shown in Figure 1.

[0014] Figures 7a and 7b are illustrations of device magnetization orientations corresponding to the first method.

[0015] Figure 8 is an illustration of a second method of performing a read operation on the memory device shown in Figure 1.

[0016] Figure 9a-9e and 10a-10e further illustrate the second method.

[0017] Figure 11 is an illustration of a circuit for implementing the second method.

[0018] Figures 12a and 12b are timing diagrams for the circuit shown in Figure 11.

[0019] Figure 13 is an illustration of an MRAM device according to the present invention.

[0020] Figure 14 is an illustration of an alternative MRAM device according to the present invention.

[0021] Figure 15 is an illustration of the alternative MRAM device during a read operation.

DETAILED DESCRIPTION

[0022] Referring to Figure 1, a magnetic memory device 10 includes a magnetic tunnel junction 11 having a data layer 12, a reference layer 14, and an insulating tunnel barrier 16 between the data and reference layers 12 and 14. The data layer 12 has a magnetization (represented by the vector M1) that can be oriented in first and second directions, typically along the easy axis (EA1) of the data layer 12. The reference layer 14 has a magnetization (represented by the vector M2) that can be oriented in first and second directions, typically along its easy axis (EA2). The easy axes (EA1, EA2) are shown as extending along the x-axis.

[0023] If the magnetizations vectors (M1 and M2) of the data and reference layers 12 and 14 are pointing in the same direction, the orientation of the magnetic tunnel junction 11 is said to be "parallel." If the magnetization vectors (M1 and M2) of the data and reference layers 12 and 14 are pointing in opposite directions, the orientation of the magnetic tunnel junction 11 is said to be "anti-parallel." These two

stable orientations, parallel and anti-parallel, may correspond to logic values of '0' and '1.'

[0024] The insulating tunnel barrier 16 allows quantum mechanical tunneling to occur between the data and reference layers 12 and 14. This tunneling phenomenon is electron spin dependent, causing the resistance of the magnetic tunnel junction 11 to be a function of the relative orientations of the magnetization vectors (M_1 and M_2) of the data and reference layers 12 and 14. For instance, resistance of the magnetic tunnel junction 11 is a first value (R) if the magnetization orientation of the magnetic tunnel junction 11 is parallel and a second value ($R+\Delta R$) if the magnetization orientation is anti-parallel. The insulating tunnel barrier 16 may be made of aluminum oxide (Al_2O_3), silicon dioxide (SiO_2), tantalum oxide (Ta_2O_5), silicon nitride (SiN_4), aluminum nitride (AlN_x), or magnesium oxide (MgO). Other dielectrics and certain semiconductor materials may be used for the insulating tunnel barrier 16. Thickness of the insulating tunnel barrier 16 may range from about 0.5 nanometers to about three nanometers.

[0025] Coercivity (H_{C1}) of the data layer 12 is much higher than coercivity (H_{C2}) of the reference layer 14 (see Figure 2, which shows hysteresis loops L1 and L2 for the data and reference layers 12 and 14, respectively). The coercivity (H_{C1}) of the data layer 12 may be at least 2-5 times greater than the coercivity of the reference layer 14. For example, the coercivity (H_{C1}) of the data layer 12 may be about 25 Oe, and the coercivity (H_{C2}) of the reference layer 14 may be about 5 Oe. Thus, the reference layer 14 is considered "softer" than the data layer 12 because its magnetization vector (M_2) is much easier to flip.

[0026] The data layer 12 is made of a ferromagnetic material. The reference layer 14 is implemented as a synthetic ferrimagnet (SF), also known as an artificial antiferromagnet.

[0027] Referring to Figures 3a and 3b, the SF reference layer 14 may include first and second ferromagnetic layers 50 and 52 separated by a metallic spacer layer 54. The ferromagnetic layers 50 and 52 may be made of a material such as CoFe, NiFe or Co, and the spacer layer 54 may be made of an electrically conductive, magnetically non-conductive material such as Ru, Re, Rh or Cu. There is a strong interlayer exchange coupling between the two ferromagnetic layers 50 and 52. The magnitude of

this coupling and also its sign (whether it is positive or negative) is a function of the spacer thickness/material and ferromagnetic layer materials and thicknesses. The coupling is negative, i.e., the magnetization vectors of the two ferromagnetic layers 50 and 52 are anti-parallel.

[0028] The size of the bit, its shape and the thickness of a particular FM layer decide its coercivity, i.e., the x-axis component of the hysteresis loop. One of the hysteresis loops is shown in Figure 4. The total volume of the FM layer and the unit magnetization (the magnetic moment per unit volume) of the layer material determine the total magnetization or moment of the layer, i.e., the y-axis component of the hysteresis loop.

[0029] The coercivities of the two FM layers 50 and 52 may be slightly different (e.g., 10 ± 5 Oe, 50 ± 10 Oe). The coercivity of the SF reference layer 14 is lower than that of the individual FM layers 50 and 52. Since the magnetizations of the two FM layers 50 and 52 point in opposite directions, their moments tend to cancel each other, i.e., $M_{SF} = M_1 - M_2$, where M_1 is the magnetic moment of the first ferromagnetic layer 50, M_2 is the magnetic moment of the second ferromagnetic layer 52, and M_{SF} is the resultant magnetic moment of the SF reference layer 14. Resulting is the hysteresis loop of Figure 5.

[0030] Thickness of the spacer layer 54 may be between about 0.2 nm and 2 nm. Each ferromagnetic layer 50 and 52 may have, for example, a coercivity of about 10-100 Oe and similar hysteresis loops. If, for example, the thickness of the first layer 50 is three nanometers and the thickness of the second layer 52 is four nanometers, the resulting imbalance will result in the hysteresis loop of equivalent to a 1 nm thickness. The resulting coercivity can be controlled to less than 10 Oe by varying the ratio of thickness of the first and second layers 50 and 52. This low coercivity allows the magnetization vector of the SF reference layer 14 to be switched easily between the orientations shown in Figures 3a and 3b.

[0031] Exchange coupling between the magnetization vectors of the two FM layers 50 and 52 is very strong. Consequently, a very large magnetic field (e.g., 4000 Oe) would be needed to decouple the magnetization vectors of the ferromagnetic layers 50 and 52.

[0032] Exemplary SF reference layers 14 are as follows.

	Example 1	Example 2	Example 3	Thickness (nm)
Layer 50	CoFe	NiFe	Co	3
Spacer 54	Ru	Ru	Ru	0.75
Layer 52	CoFe	NiFe	Co	4

[0033] The SF reference layer is not limited to the three-layer structure just described. The SF reference layer may include more than three layers. For example, the SF reference layer may include the following five reference layers: FM1/Ru1/FM2/Ru2/FM3, all having different thicknesses.

[0034] The SF reference layer may be clad with a ferromagnetic material such as NiFe. The cladding can reduce stray fields and reduce read/write current requirements (by concentrating the magnetic fields generated during read and write operations).

[0035] Returning to Figure 1, a first conductor 18 extending along the x-axis is in contact with the data layer 12. A second conductor 20 extending along the y-axis is in contact with the reference layer 14. The first and second conductors 18 and 20 are shown as being orthogonal. Above the second conductor 20 is a third conductor 22, which also extends along the y-axis. An electrical insulator 24 (e.g., a layer of dielectric material) separates the second and third conductors 20 and 22. The conductors 18, 20 and 22 are made of an electrically conductive material such as aluminum, copper, gold or silver.

[0036] Data may be written to the magnetic tunnel junction 11 by supplying write currents to the first and second conductors 18 and 20. The current supplied to the first conductor 18 creates a magnetic field about the first conductor 18, and the current supplied to the second conductor 20 creates a magnetic field about the second conductor 20. The two magnetic fields, when combined, exceed the coercivity (H_{C1}) of the data layer 12 and, therefore, cause the magnetization vector ($M1$) of the data layer 12 to be set in a desired orientation (the orientation will depend upon the directions of the currents supplied to the first and second conductors 18 and 20). The magnetization

will be set to either the orientation that corresponds to a logic '1' or the orientation that corresponds to a logic '0'. Because the coercivity (H_{C2}) of the reference layer 14 is less than that of the data layer 12, the combined magnetic fields cause magnetization ($M2$) of the reference layer 14 to assume that same orientation as the magnetization ($M1$) as the data layer 12.

[0037] After write currents are removed from the conductors 18 and 20, the magnetization vector ($M1$) of the data layer 12 retains its orientation. The magnetization vector ($M2$) of the reference layer 14 may or may not retain its orientation. If the reference layer 14 is "ultra-soft," it will lose its magnetization orientation when the write currents are removed from the first and second conductors 18 and 20.

[0038] The third conductor 22 may be used to assist with write operations. By supplying a current to the third conductor 22 during write operations, the resulting magnetic field about the third conductor 22 combines with the other two magnetic fields to help set the magnetization vector ($M1$) of the data layer 12 in the desired orientation.

[0039] Figure 6 illustrates a first method of reading the magnetic memory device 10. A current is supplied to the third conductor 22, and the resulting magnetic field causes the magnetization vector ($M2$) of the reference layer 14 to assume a specific orientation (block 110). The resulting magnetic field does not affect the magnetization vector ($M1$) of the data layer 12. Since the coercivity (H_{C2}) of the reference layer 14 is low, the magnitude of the third conductor current may be low.

[0040] As the current is supplied to the third conductor 22, a voltage is applied across the magnetic tunnel junction 11 (block 110). The first and second conductors 18 and 20 may be used to apply the voltage across the magnetic tunnel junction 11. The voltage causes a sense current to flow through the magnetic tunnel junction 11.

[0041] The resistance of the magnetic tunnel junction 11 is measured by sensing the current flowing through the magnetic tunnel junction 11 (block 112). The sensed current is inversely proportional to the resistance of the magnetic tunnel junction 11. Thus $I_s = V/R$ or $I_s = V/(R + \Delta R)$, where V is the applied voltage, I_s is the sensed current, R is the nominal resistance of the device 10, and ΔR is the change in resistance

caused by going from a parallel magnetization orientation to an anti-parallel magnetization orientation

[0042] Reference is now made to Figures 7a and 7b. Consider a magnetic tunnel junction 11 having a nominal resistance (R) of 1 Mohm, and a tunneling magneto-resistance of 30%. A read current (I_R) is depicted as flowing into the third conductor 22. The read current (I_R) causes the magnetization vector (M_2) of the reference layer 14 to point to the left. If the measured resistance $R=1$ Mohm, the data layer 12 stores a first logic value (Figure 7a). If the measured resistance $R=1.3$ Mohm, the data layer stores a second logic value (Figure 7b). Thus, by setting the magnetization of the reference layer 14 to a known orientation and measuring the resistance of the device 10 (either R or $R+\Delta R$), the logic value stored in the magnetic memory device 10 is determined.

[0043] Figure 8 illustrates a second method of reading the magnetic memory device 10. A bipolar pulse is applied to the third conductor 22 (block 210), and transition of junction resistance is examined (212). The direction of the transition (that is, going from high to low, or low to high) indicates the magnetization orientation of the data layer 12 and, therefore, the logic value stored in the magnetic memory device 10.

[0044] Figures 9a-9e further illustrate the second method in connection with a data layer 12 that stores a logic '0.' A bipolar pulse 250 is applied to the third conductor 22 (Figure 9a). The bipolar pulse 250 has a positive polarity 252 (corresponding to a logic '0') followed by a negative polarity 254 (corresponding to a logic '1'). The positive polarity 252 orients the magnetization of the reference layer 14 in the same direction as that of the data layer 12 (Figure 9b), whereby the magnetization orientation of the device 10 is parallel and its resistance value is R_p . Then the negative polarity 254 orients the magnetization vector (M_2) of the reference layer 14 in the opposite direction (Figure 9c), whereby the magnetization orientation of the device 10 is anti-parallel and its resistance value is $R+\Delta R$ or R_{ap} . Thus the resistance of the device 10 transitions from low to high (Figure 9d). The low-to-high transition indicates that a logic '0' is stored in the memory device 10. The corresponding sense current (I_s) is shown in Figure 9e.

[0045] Figures 10a-10e illustrate the second method in connection with a data layer 12 that stores a logic '1.' The same bipolar pulse 250 is applied to the third

conductor 22 (Figure10a). The magnetic memory device transitions from an anti-parallel magnetization orientation (Figure10b) to a parallel magnetization orientation (Figure10c), whereby the resistance of the magnetic memory device 10 transitions from high to low (Figure10d). Thus the high-to-low transition indicates that a logic '1' is stored in the magnetic memory device 10. The corresponding sense current (I_S) is shown in Figure10e.

[0046] The bipolar read operation references to itself. Therefore, this dynamic approach is insensitive to resistance variations across different devices.

[0047] The bipolar pulse is not limited to a single positive polarity followed by a single negative polarity, nor is it limited to a positive polarity that corresponds to a logic '0' and a negative polarity that corresponds to a logic '1'. For example, a positive polarity could just as easily correspond to a logic '1', a bipolar pulse could begin with a negative polarity and transition to a positive polarity, etc.

[0048] A simple sense amplifier 310 for detecting the resistance transition is shown in Figure 11. The sense current (I_S) flowing through the magnetic tunnel junction 11 is supplied to a sense amplifier 312. First and second outputs of the sense amplifier 312 provide a voltage (V_{SENSE}) that is proportional to sense current magnitude. The first output is supplied to a first input (IN+) of a comparator 316. The second output of the sense amplifier 312 is supplied to a delay element 314, which has a delay of several nanoseconds. An output of the delay element 314 is supplied to a second input (IN-) of the comparator 316. The comparator 316 compares the sense voltage (V_{SENSE}) at the first comparator input (IN+) to the delayed sense voltage at the second comparator input (IN-). An output (VOUT) of the comparator 316 indicates the logic state stored in the magnetic memory device 10.

[0049] Figures 12a and 12b are timing diagrams for the circuit of Figure 11. Figure 12a corresponds to Figures 9a-9e, and Figure 12b corresponds to Figures 9a-9e.

[0050] The magnetic memory device 10 has a simpler structure than a conventional SDT junction. The magnetic memory device 10 is simpler to fabricate than an SDT junction because seed layers and an AF pinning layer are not needed. Annealing of the data layer to set the easy axis may still be performed, but it is done at

lower temperatures and is less critical. In addition, the complexity of the deposition process is significantly reduced. Another advantage is that the data layer 12 is on top of a metal conductor, resulting in a more uniform data film and, therefore, better magnetic response and manufacturability (in terms of greater uniformity over a wafer).

[0051] Reference is now made to Figure 13, which illustrates an MRAM device 410 including an array 12 of magnetic tunnel junctions 11. The magnetic tunnel junctions 11 are arranged in rows and columns, with the rows extending along an x-direction and the columns extending along a y-direction. Only a relatively small number of the magnetic tunnel junctions 11 is shown to simplify the illustration of the MRAM device 410. In practice, arrays of any size may be used.

[0052] Traces functioning as word lines 18 extend along the x-direction in a plane on one side of the array 12. The word lines 18 are in contact with the data layers 12 of the magnetic tunnel junctions 11. Traces functioning as bit lines 20 extend along the y-direction in a plane on an adjacent side of the array 12. The bit lines 20 are in contact with the reference layers 14 of the magnetic tunnel junctions 11. There may be one word line 18 for each row of the array 12 and one bit line 20 for each column of the array 12. Each magnetic memory tunnel junction 11 is located at a cross point of a word line 18 and a bit line 20.

[0053] Traces functioning as read lines 22 also extend along the y-direction. The read lines 22 are on top of, and insulated from, the bit lines 20. (In the alternative, the read lines 22 may be beneath the bit lines 20, on top of or beneath the word lines 18, along rows or columns, etc.) The read lines 22 are independent of the word and bit lines 18 and 20.

[0054] The MRAM device 410 also includes first and second row decoders 414a and 414b, first and second column decoders 416a and 416b, and a read/write circuit 418. The read/write circuit 418 includes a sense amplifier 420, ground connections 422, a row current source 424, a voltage source 426, and a column current source 428.

[0055] During a write operation on a selected magnetic tunnel junction 11, the first row decoder 414a connects one end of a selected word line 18 to the row current source 424, the second row decoder 414b connects an opposite end of the selected

word line 18 to ground, the first column decoder 416a connects one end of a selected bit line 20 to ground, and the second column decoder 416b connects the opposite end of the selected bit line 20 to the column current source 428. As a result, write currents flow through the selected word and bit lines 18 and 20. The write currents create magnetic fields, which cause the magnetic tunnel junction 11 to switch. The column decoders 416a and 416b may also cause a write current to flow through the read line 22 crossing the selected magnetic tunnel junction 11. This third write current creates an additional magnetic field that assists in switching the selected magnetic tunnel junction 11.

[0056] During a read operation on a selected magnetic tunnel junction 11, the first row decoder 414a connects the voltage source 426 to a selected word line 18, and the first column decoder 416a connects a selected bit line 20 to a virtual ground input of the sense amplifier 420. As a result, a sense current flows through the selected magnetic tunnel junction 11 to the input of the sense amplifier 420. In the meantime, the first and second column decoders 416a and 416b cause either a steady read current or a bipolar current pulse to flow through the read line 22 crossing the selected magnetic tunnel junction 11. If a steady read current is supplied to the selected read line 22, the resistance state of the selected magnetic tunnel junction 11 is sensed by the sense amplifier 420. If a bipolar pulse is supplied to the selected read line 22, the transition of the junction resistance is examined by the sense amplifier 420 (a sense amplifier 420 for examining the transition of the junction resistance may have the same configuration as the sense amplifier 312 shown in Figure 11).

[0057] The magnetic tunnel junctions 11 are coupled together through many parallel paths. The resistance seen at one cross point equals the resistance of the magnetic tunnel junction 11 at that cross point in parallel with resistances of magnetic tunnel junctions 11 in the other rows and columns. Thus the array 12 of magnetic tunnel junctions 11 may be characterized as a cross point resistor network.

[0058] Because the magnetic tunnel junctions 11 are connected as a cross point resistor network, parasitic or sneak path currents can interfere with the read operations on selected magnetic tunnel junctions 11. Blocking devices such as diodes

or transistors may be connected to the magnetic tunnel junctions 11. These blocking devices can block the parasitic currents.

[0059] In the alternative, the parasitic currents may be dealt with by using an "equipotential" method disclosed in assignee's U.S. Patent No. 6,259,644. If configured to use the equipotential method, the read/write circuit 418 may provide the same potential to the unselected bit lines 20 as the selected bit line 20, or it may provide the same potential to the unselected word lines 18 as the selected bit line 20.

[0060] Because the read lines 22 are electrically insulated from the bit lines 20, they do not add to the resistive cross coupling of the magnetic tunnel junctions 11. Therefore, an equal potential is not applied to the read lines 22.

[0061] Figure 13 shows an MRAM device 410 with three different types of traces: word lines 18, bit lines 20, and read lines 22. However, the present invention is not so limited. For example, an MRAM device according to the present invention may have only two different types of traces: word lines 18 and bit lines 20.

[0062] Reference is made to Figure 14, which illustrates an MRAM device 510 including word lines 18 and bit lines 20, but not read lines 22. Magnetic tunnel junctions 11 are located at cross points of word and bit lines 18 and 20.

[0063] Additional reference is made to Figure 15, which illustrates a read operation using only the word and bit lines 18 and 20. The first row decoder 514a connects the voltage source 526 to a selected word line 18, and the first column decoder 516a connects one end of a selected bit line 20 to a virtual ground input of the sense amplifier 520. As a result, a sense current (I_S) flows through the selected magnetic tunnel junction 11 to the sense amplifier 520. The second column decoder 516b connects the column current source 528 to the other end of the selected bit line 20. As a result, a read current (I_R) flows through the selected bit line 20 to the sense amplifier 520. The read current (I_R) sets the magnetization vector of the reference layer. The sense amplifier 520 senses the sum of sense and read currents ($I_S + I_R$). Since the magnitude of the read current (I_R) is known, the magnitude of the sense current (I_S), and hence the resistance and logic states of the magnetic tunnel junction 11, can be determined.

[0064] Although the present invention was described in connection with a TMR device, it is not so limited. The present invention may be applied to other types of magneto-resistive devices that have similar operational characteristics. For instance, the present invention may be applied to giant magneto-resistive (GMR) devices. A GMR device has the same basic configuration as a TMR device, except that data and reference layers are separated by a conductive non-magnetic metallic layer instead of an insulating tunnel barrier. Exemplary spacer layer metals include gold, silver and copper. The relative orientations of the data and reference magnetization vectors affect in-plane resistance of a GMR device.

[0065] The present invention is not limited to GMR and TMR devices. For instance, the present invention may be applied to top and bottom spin valves.

[0066] Although several specific embodiments of the present invention have been described and illustrated, the present invention is not limited to the specific forms or arrangements of parts so described and illustrated. Instead, the present invention is construed according to the claims the follow.